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DESIGN AND DEVELOPMENT OF HELICOPTER EXTERNAL CARGO SLING LEGS MADE WITH KEVLAR

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APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This report documents a program of design, fabrication, and test for the purpose of developing manageable lightweight helicopter external cargo slings made of Kevlar fibers. Three sling assembly capacities, 10K, 25K and 40K-pound, were fabricated to meet the external load handling requirements of the Army and Marine Corps. In the two higher capacity assemblies, problems were experienced in achieving an efficient end termination which resulted in the overdesign of the basic sling rope. This program demonstrates the need for additional R&D effort to develop a more efficient end termination and associated hardware for Kevlar slings.

Richard E. Lane of the Military Operations Technology Division was the project engineer for this effort.

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Quantitive equations and graphs for torque balanced Kevlar rope constructions have been applied to the preliminary design of sling legs for heavy lift helicopters. Fifty-one 14-foot sling legs were made and tested to determine minimum break strengths for the 10,000-lb (10K), 25,000-lb (25K), and 40,000-lb (40K) load capacity assemblies. Three 10K assemblies using torque balanced Kevlar rope with eye-spliced terminations over No. 2 SLIP-THRU thimbles were delivered to USAAMRDL (AVSCOM) for field testing. Three 25K and four 40K assemblies made by an alternative torque balanced Kevlar grommet design were also delivered for field testing.

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Block 20. Abstract - continued.

Three 10K assemblies were delivered to USAAMRDL (AVSCOM) for field testing. The four sling legs on each of these 10K assemblies were made using torque balanced Kevlar rope with eye-spliced terminations over No. 2 SLIP-THRU thimbles. The three 25 K and four 40K assemblies delivered for field testing [illegible] by an alternative torque balanced Kevlar grommet design with No. 3 and 4 size thimbles.

PREFACE

This report presents the procedures for fabricating Heavy Lift Helicopter Sling Legs using Kevlar, DuPont Company's patented aramid fibers. Also provided are analytical results, design concepts, and test data for three load levels of 10,000 lb, 25,000 lb and 40,000 lb , the assembly safe working loads.

The work was sponsored by the Eustis Directorate, U.S.Army Air Mobility Research and Development Laboratory (USAAMRDL),* Fort Eustis, Virginia, and was performed by the Advanced Products Division of the Cortland Line Company, Cortland, New York, under Contract DAAJ02-76-C-0025 during the period July 1976 through January 1978.

The Army technical representative was Richard Lane.

The following Cortland Line personnel contributed to the program:

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1.0 SUMMARY

Quantitive equations and graphs for torque-balanced Kevlar rope constructions have been applied to the preliminary design of sling legs for heavy lift helicopters. Fifty-one 14-foot sling legs were made and tested to determine minimum break strengths for the 10,000-lb (10K), 25,000-lb (25K), and 40,000-lb (40K) load capacity assemblies. Three 10K assemblies with sling legs made from the torque balanced Kevlar rope which had ten break strength tests over the 17,200-lb design minimum were delivered for field testing. The break strength tests were on sling leg prototypes that used the preliminary design construction and eye-spliced terminations with No. 2 SLIP-THRU (Brewer-Tichner Company) thimbles.

The sling legs for the three 25K and four 40K assemblies delivered to USAAMRDL were, however, alternatively made using a grommet design. The slip and erratic tensile properties of eye splices limited to the 14-ft span made it questionable to employ the planned preliminary specifications. The grommet design successfully met the break strength requirement with minimum weight, but reduced the efficiency of the Kevlar construction from about 90% for the 10K legs to 70% for the 25K and 40K legs.

The 25K sling legs were above the 36,000-lb minimum break strength, using No.3 SLIP-THRU thimbles. The 40K assembly legs were made to exceed 56,000-lb break strength, using No. 4 SLIP-THRU thimbles.

2.0 INTRODUCTION

2.1 PREVIOUS RELATED PROGRAMS

In 1974, the Eustis Directorate, USAAMRDL, sponsored the testing of Kevlar cables. The results of the tensile, fatigue, and abrasion tests of that program are given in the Army Materials and Mechanics Research Center Report AMMRC. (Ref 1). It concluded that the Cortland Line Company's sling legs with impregnated polyester braided jackets were superior to extruded polyurethane jackets in abrasion tests. These were cyclic tests done over ceramic pipe. It also concluded that fatigue loading did not degrade the Kevlar and that Cortland sling leg material could be accepted for use.

A series of studies were also done on the early Cortland samples by the Engineering Mechanics Section of the National Bureau of Standards. (Ref 2).

The work at AMMRC and at NBS was done on 54-in-long samples of Kevlar cables having Parallel Kevlar Strands (CORMAR III). There were three series of samples with break strength requirements of 17,200-lb, 36,000-lb, and 56,000-lb. All of the cables were terminated with standard forged steel socket fittings, using an epoxy potting system. The fatigue tests showed a number of failures at or near the terminations due to pull out, or leakage of resin, etc. It was concluded at USAAMRDL that these potted terminations, while desirable for sling legs, did not have the reliability of conventional splice eye terminations over thimbles. The spliced types could be lighter and better adapted to fitting on shackles and hooks.

During previous USAAMRDL efforts, standard hardware was developed for nylon and steel sling legs. (Ref 3, 4).

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1. E. C. Goeke, Abrasion Resistance and Fatigue Characteristics of Kevlar Sling Leg Structures, AMMRCTN-76-4. Army Materials Lab, Watertown, Mass., Feb. 1976.

2. M.Halsey and L. Mordfin, Fatigue and Weatherability Studies of Aramid Fiber Rope Slings, NBSIR 76-1159, National Bureau of Standards, Gaithersburg, Md., September 1976.

3. Walter E. Huebner, Design Guide for Load Suspension Points, Slings, and Aircraft Hard Points, Sikorsky Aircraft Div., United Aircraft Corp., USAAMRDL Technical Report 72-36, Eustis Directorate, U.S.Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, July 1972, AD747814.

4. H. T. Hone, W. E. Huebner, and D. J. Baxter, Development of Cargo, Slings With Nondestructive Checkout Systems, Sikorsky Aircraft Div., United Aircraft Corp., USAAMRDL Technical Report 73-106, Eustis Directorate, U.S.Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, February 1974, AD777497.

2.2 ADVANCED TECHNOLOGY SLING LEG

The hardware to be delivered with the assemblies (Three 10K, three 25K, and four 40K) for this present contract were supplied by USAAMRDL from the previous 1974 project. This consisted of apex fittings (large shackles), grab hooks (hooks for chain), and standard one-half-inch steel chain. The delivered assemblies were to be made up of four Kevlar sling legs on each apex fitting, with a grab hook and chain on each leg.

The USAAMRDL advanced sling leg contract called for standard commercial type SLIP-THRU thimbles. The sling legs for the three sizes of assemblies were to use Kevlar ropes that were 0.5 in., 0.7 in. and 0.9 in. in diameter, plus outer jackets. This meant that the thimbles had to be for 1/2 in., 3/4 in. and 1 in. ropes. There was no way for these size thimbles (BTC No. 3, 4 and 5) fit the grab hooks, unless adapter rings or shackles were used. This problem was solved as a side benefit of the grommet designs, which permitted the use of smaller thimble sizes for the 25K and 40K assemblies.

2.3 STANDARD CONSTRUCTIONS FOR ROPE AND CABLE

The terms rope and cable are used interchangeably in industry and literature, and vary with the materials, engineering field, or factory. Steel wire is assembled in a cabling machine to form the wire rope construction. This can be on one or more layers with different lay angles or pitch. Usually a rope is a mechanical tensile member, while a cable is electrical or electromechanical. The steel armored or double armored cable means the steel strength member is on the outside. There are many variations and methods for splicing, terminating, or joining with standardized sockets (spelter, and new epoxy potting), swagged fitting, nichropress, clips, splicing, and a multitude of specialized mechanical gripping techniques, and any of several types of splices common in the trade.

With fibers, natural or synthetic, one forms a yarn as a continuous bundle of the fibers. The measure of size peculiar to the textile and fiber industry is denier, the weight in grams of 9000 meters of filament or yarn. The synthetic fibers are produced with dies or spinerettes with many holes, sometimes in the thousands, and these fibers are processed and packaged normally with little or no twist. These parallel fiber bundles or yarns usually are twisted in subsequent processing, and also plied. Ply means the twisting or gathering together of two or more yarns to increase the size and strength of the basic strength member, which is the strand.

One therefore goes from the fiber or filament to the yarn, and then to a strand. The latter would be comparable to the wire strand. This strand is then used to construct a cord or rope. In this case, a rope construction is the highly twisted and flexible design associated with fiber rope as distinct from wire rope.

Kevlar is a synthetic organic fiber that can be handled in many machines used for textile materials. Yet it is strong enough to be used to replace steel, and frequently it is used on machines and in applications that specify steel ropes or cables. In general, the Kevlar is not best used in conventional synthetic fiber rope construction because the high twist degrades the strength potential. The Kevlar is an aramid class of synthetic fiber, as is Nomex, made only by DuPont. It is standardized as 12 micron filament (0.00047 ins d. or 12×10^{-6} meters). It is available as either Kevlar 29 with an elastic modulus of 8 million psi (55×10^9 Pa) Kevlar 49 with 18 million psi (124×10^9 Pa). The filaments have approximately a 500,000 psi (3.5×10^9 Pa) tensile strength. The Kevlar 29 yarns come in sizes (deniers) that have average or nominal break strengths of 8, 16, 40, 60, and 600 lb (Ref 5).

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5. E. Scala, CORMAR Kevlar Ropes and Cables, Sea Technology Journal (July 1977, p 13 to 16)

3.0 STRENGTH EFFICIENCY ANALYSIS OF KEVLAR CABLES FOR SLING LEGS

3.1 BACKGROUND

A multifilament tensile member must have a helical construction to allow for a flexible rope, prevent local buckling or kinking, and have optimum efficiency. Several designs were initially considered using 15,000-denier Kevlar 29, which would have the required torque balanced construction. The assumption was that three continuous ropes would be produced, one for each break strength required. The rope would then be cut to the lengths needed to form the 14-foot sling legs with spliced loops at both ends.

The simplest rope construction to meet the above requirement would have a large twisted bundle of yarns as a core, with an outer layer of yarns having the opposite direction of twist and lay. An alternate design would have the same core, a large twisted bundle, but the outer layer would have strands as tension members layed with a helix angle opposite to the twist of the interior bundle. These strands would be made from multiples or plys of the 15,000-denier Kevlar 29, each strand twisted to attain the optimum strength. As a guide to the manufacturer, the DuPont Company has published the empirical formula for the twist to use for maximum strength as a function of Kevlar yarn denier twists per inch (tpi) = $73/\sqrt{\text{denier}}$. This twist multiplier relationship is intended to apply to the yarns of smaller denier (200 d to 1500d) and is used for all types of yarns with different constants. It is only a rough guide for the plying and twisting of strands made up of two or more yarns of 15,000 d.

The cores for the two rope designs mentioned above would have twenty or more yarns of 15,000 d. For a large diameter line or rope, a massive core of twisted yarn does not permit the filament migration, which is the principal requirement for optimum and successful use of the high-strength fiber material. (References 6 through 11)

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6. H. E. Daniels, The Statistical Theory of Strength of Bundles of Threads 1, Proc. Roy. Soc. A183 (1945) 405-435.

7. B. D. Coleman. On the Strength of Classical Fibres and Fibre Bundles. J. Mech. Phys. Solids, 7 (1958) 60-70.

8. S. L. Phoenix and H. M. Taylor, The Asymptotic Strength Distribution of a General Fiber Bundle, J. Adv. Appl. Prob. 5 (1973) 200-216.

9. S. L. Phoenix, Probabilistic Strength Analysis of Fiber Bundle Structures, Fibre Sci., and Tech. 7 (1974) 15-31.

10. J.W.S.Hearle, P. Grosberg, and S. Backer, Structural Mechanics of Fibers, Yarns and Fabrics. Wiley-Interscience, N.Y. (1069)

11. S. L. Phoenix, Probalistic Theory of Time Dependent Failure of Fiber Bundles, Proceedings Oceans '76 MTS-IEEE, (1976) AF1-11.

The design that is optimum, and which can be analyzed, calls for the cabling of strands for a core balanced by an outer counterhelix strand layer. Statistical variations have been derived that are useful in establishing minimum strength values with high reliability. The basic requirement is the data on the strand strengths. This is experimental data that has to be accumulated with the building and testing of strands. Some data was already available from previous work, and was used for the preliminary analysis and the design specifications.

3.2 PRELIMINARY DESIGN ANALYSIS

The preliminary design specifications were attained by an iterative calculation of strand sizes and break strengths, the number of strands in the "inner and outer layers", and the respective strand lay angles. The example discussed here refers to the sling legs for the 10,000-lb SWL Sling Assembly, which calls for an ultimate break strength of 17,200-lb for the manufactured rope and legs. This latter specification should properly read minimum break strength. To be technically meaningful it should specify the percentage survivability. In engineering applications, the accepted 3 sigma variation means a 99.8% survivability, which does not include the manufacturing efficiency factor subsequently applied to the cable design.

To outline the analytical procedure used for the smaller sling leg, we started with the known 600-lb average break strength for 15,000 denier Kevlar 29, which is the commercially available size for manufacturing these cables or ropes. The 15,000 d. yarn from DuPont is processed at Cortland to form strands that are multiples of this yarn by impregnating and twisting for optimum strengths. These strands do not always have the simple multiple strengths, nor do they have the same scatter or coefficient of variation in strength. In theory these large multiple strands have to have a larger variation and lower average from the nature of material used, namely a much larger population of filaments of which the Kevlar yarn is made.

To build up the 17,200-lb minimum break strength (for the 10K SWL Assemblies) from multiples of the 15,000 d. yarn, a design was developed that had a seven-strand core, with three ends of yarn per strand, and a 12-strand outer layer with each strand made with two ends of yarn. If these strands, experimentally have average strengths of 1800 lb (3 ends of yarn) and 1200 lb. (2 ends of yarn), the product would be (7x1800 lb) + (12x1200 lb) or 27,000-lb. The efficiency of the cable needed to be established; it needed to be determined if the minimum strength (3 sigma, or 99.8% probability of success) was above 17,200-lb; and the lay angles for the inner and outer layers for torque balance had to be selected.

A reasonable lay angle for the inner layer is 10° which, based on Figure 1, calls for the outer layer to be about 4°. The mathmetics and equation for this curve can be found in References 8, 9, and 11.

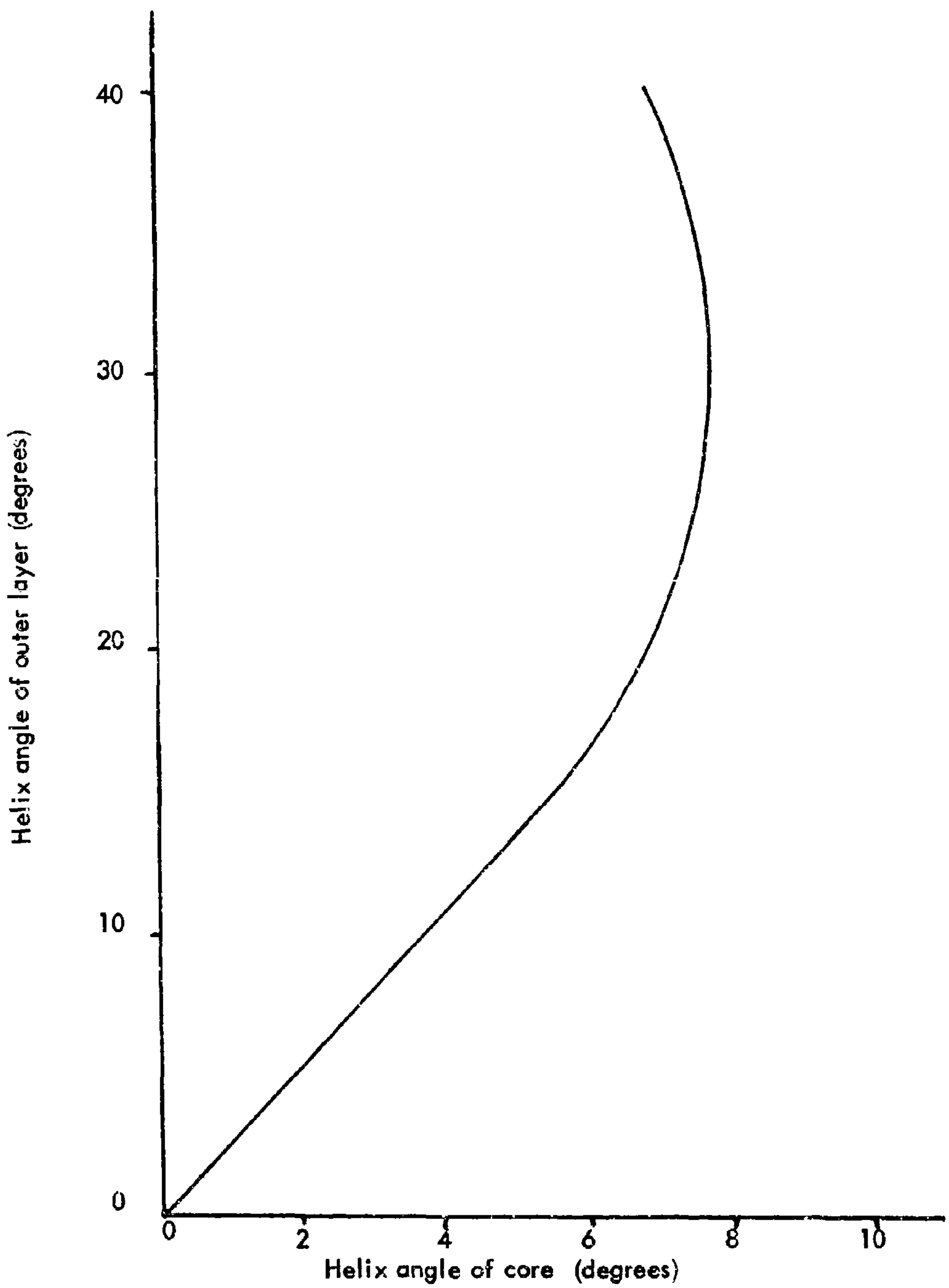

FIGURE 1. RELATIONSHIP BETWEEN HELIX ANGLES OF CORE AND OUTER LAYER TO ACHIEVE TORQUE BALANCE. (From Reference 9)

This curve for torque balance has been used for preliminary cable fabrication, but a computer program for torque balance should be used when experimental verification is available based on hundreds of tests, or sufficient to be statistically meaningful.

From Figure 2, with a coefficient of variation for the strand of about 6% (plotted as P = 0.062) and a 10° core strand lay angle, the cable efficiency is 0.845 and the effective strand cross section is increased at 10° by 1.008. The latter is not significant and is well within limits of error. The cable mean breaking strength is therefore predicated as (0.845 x 1.008 x 27,000 lb.) = 22,998 lb. However, this is the average value and not the minimum, so the coefficient of variation must be taken into account, i.e., the probable scatter.

It is known that the scatter for the yarn is about 6% and that in forming the cable with strands helically wound, this scatter tends to be decreased by the synergistic effects of interfilament shear. Assuming this reduces the coefficient of variation of the breaking strength of the cable to 4%, then for the 3 sigma reliability, the break strength would be 3 x 4% or 12% less than the cable mean breaking strength, or (22,998 lb. x 0.88) = 20,238 lb.

At this point, the manufacturing efficiency factor has to be accounted for; that is, the effects of stranding or cabling to form the core and outer layer, such as uniformity of tension, lay angles, friction effects, and manufacturing variables possible along the total lengths of the rope or cable. This may be about a 0.9 factor, which brings the probable minimum break strength of the cable to about 18,200 lb. Therefore, a satisfactory design to build the cable for a desired minimum of 17,200 lb. Relative to the calculated average strength of 27,000 lb, this would be 67%. The testing of the preliminary samples for these sling legs may well be higher than predicted here based on previous experience, but this was the safe design to proceed with, recognizing that many hundreds of tests would be required for assurance of the minimum strength value.

3.3 PRELIMINARY DESIGNS

The proposed design for the rope to make sling legs for the 10,000-lb SWL Sling Assembly could therefore be a core of 7 strands of (3x15,000 d.) Kevlar 29 with a 10° lay angle and an outer layer of 12 strands of (2x15,000 d.), with the outer layer at about 4°. Since the details of the strand construction or number of strands are not critical to the design calculations, strand sizes and numbers can be varied. Similar calculations were made for the 25K and the 40K assemblies as preliminary design specifications. As an initial design for the 25K, the core was to be 7 strands of (6x15,000 d.) yarn at a 10° lay angle (right) with the outer layer of 12 strands of (4x15,000 d.) yarn with a 4° lay angle (left). For the 40K, the core was to be 7 strands of (10x15,000 d.) yarn at 10° lay angle with an outer layer of 12 strands of (6x15,000 d.) at 4° lay angle.

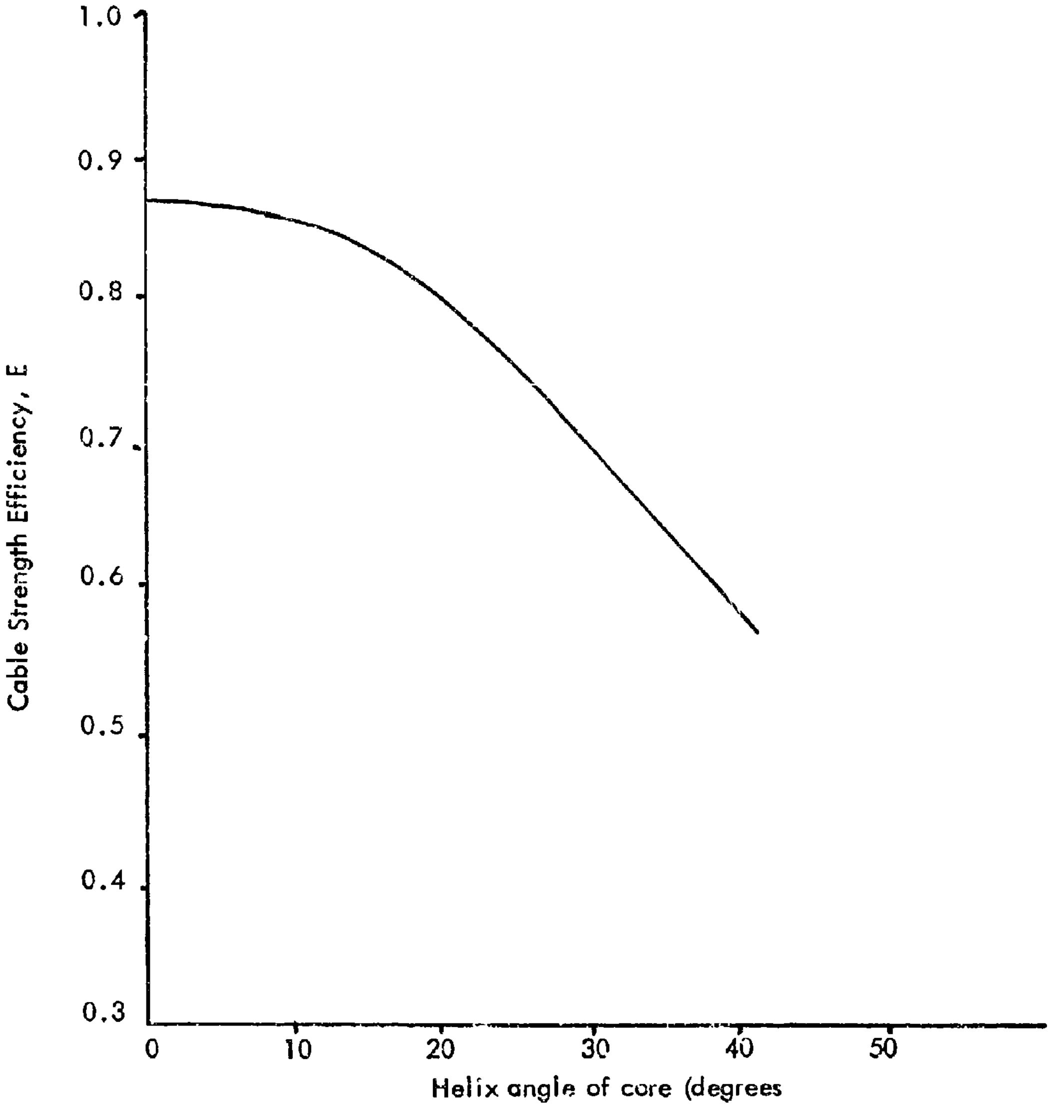

FIGURE 2. CABLE STRENGTH EFFICIENCY VERSUS CORE HELIX ANGLE (from Reference 9.)

As described in the section on preliminary testing, all of these were altered to achieve the desired strengths without employing excessive yarn, or to meet the needs of the change from a rope design to a grommet.

4.0 PRELIMINARY TEST RESULTS

4.1 THE TESTING OF KEVLAR YARNS, STRANDS, AND ROPES

Considerable testing has been done on Kevlar yarns and strands. The extensive use of 15,000 d. Kevlar 29 and plys of 2, 3 and 4 ends of this yarn during the past 5 years has generated enough data to establish average and minimum values for these size strands. Quality Control testing on yarn is useful in preventing further fabrication with faulty material, but the yarn must be tested as the strand form in which it is to be used. This has established 600-lb, 1150-lb, and 2200-lb minimums to use for 1, 2 and 4 ends of 15,000 d. Factory designations for these stock sizes are ct29/1x150, 2x150 and 4x150 respectively. (ct29 for coated and twisted Kevlar 29 and 150 for 15,000 denier).

As was evident in the design and testing of the sling leg the termination or method of gripping the ends has a very large effect on the average break strengths and on the scatter, minimums, or erratic behavior. The test values were obtained by methods intended to degrade the cable properties the least, such as capstan and pneumatic grips, and spliced loops. The latter simulates the final application. But when tested by using continuous loops, as discussed in Reference 5, the strand strength for the ct29/4x150 is 1,950-lb minimum. This will have a bearing on developments that occurred in testing the 25K and 40K sling legs.

Among the prior experience with Kevlar ropes was an 18,000-lb break strength counter-helix design (torque balanced) that had to be built for a tow cable while the early analysis and testing was in progress. Since this was so close to the 17,000-lb minimum required for the 10K design, it was considered in place of the proposed preliminary design, and is referred to below.

4.2 TESTING OF PRELIMINARY DESIGNS

The contract and design originally called for 14-ft sling legs with spliced-eye loops over slip-through thimbles.

Assembly Size	Sling Leg Break Strength	Rope Diameter	SLIP-THRU Thimble Size
10K	17,200 lb	0.5 in.	No. 3
25K	37,800 lb	0.7 in.	No. 4
40K	56,000 lb	0.95 in.	No. 5

These diameters call for slip-thru thimble sizes of No.3, No.4 and No.5, respectively, based not only on rope diameter but on the need to include sleeves of urethane to protect the loop against abrasion on these forged steel thimbles. Subsequently, smaller size thimbles were used to fit the grab hooks supplied by AVRADCOM, which had been made for earlier steel sling leg designs. The No.2 thimbles for the 10K sling legs require the loop to be squeezed into the fitting, but the test results did not indicate that this was serious. The smaller the radius of curvature at the eye or loop, the higher the compressive loading stresses at the top of a thimble, and the greater the probability of failure at a lower-than-rated strength. This discussion bears on the 25K and 40K test data.

4.3 THE 10K SLING LEG PRELIMINARY TESTS

The 10K sling legs are made from a counter-helix (torque balanced) cable. The core is made of seven strands with a 6 in. lay (right), each strand being a twisted (.5 tip) pair of 15,000 denier Kevlar 29 impregnated with a hard wax. A nylon braided jacket over this core holds the strands and acts as a lubricated abrasion barrier to the outer lay. The outer 10 strands (2x15,000 d.) are cabled at a 9 in. left lay, with an outer braided jacket of neoprene impregnated polyester. An added coating of black polyurethane has been fused over the polyester braided jacket.

The terminations are the standard counter-helical wrap for a length of 52 in. The eye splices are fitted with urethane tubing into No. 2 SLIP-THRU thimbles (BTC 745-G). Both ends are the same, with an overall length of 14 ft.

The results of ten tensile tests on 14-ft prototypes are given in Table 1. The average break strength of 19,000-lb $\pm$320-lb gives a cable efficiency of 93% (based on 1200-lb average break strength per strand of ct29/2x150). The minimum recorded break strength was 18,200-lb, well above the required 17,200-lb break strength.

This is a greater efficiency than predicted by the analysis, which is admittedly conservative. Based on the method discussed in Section 3, the average break strength would be about 17,000-lb. For a 3-sigma reliability and 90% manufacturing efficiency, the calculated minimum would be less than 14,000-lb break strength. In fact, for the guaranteed 17,200-lb minimum, the calculations would require a theoretical strength of over 25,000-lb. This would have 40 yarns of 15,000 d., rather than the 34 yarns determined experimentally.

The probable reason for the higher efficiency is the character of the eye-splice termination. The counter-helix splice used can allow the rope strands to compensate for length changes when first loaded, before the grip tightens down.

It was concluded that the prototypes met the strength and diameter requirements with minimum weight. The standard No.2 thimbles are, however, not properly designed for use with the grab hooks supplied, but there are no other commercial types available. Special designs are needed.

TABLE 1. PRELIMINARY TENSILE TESTS

10K Sling Legs (spliced-eye design) (lb)	25K Sling Legs (grommet design) (lb)
1. 19,400	1. 39,500
2. 19,400	2. 36,000
3. 19,000	3. 36,500
4. 19,200	4. 40,000
5. 18,700	5. 41,000
6. 18,200	6. 43,500
7. 18,500	7. 38,300
8. 19,000	8. 37,000
9. 19,500	9. 41,000
10. 19,100	10. 38,000
Average 19,000	Average 39,080
± 320	± 1,920

4.4 THE 25K SWL SLING LEG PRELIMINARY TESTS

The first construction and test of a 25K sling leg indicated that the 14-ft length restriction did not permit the use of the splice as used on the 10K sling legs. The splice takes a length of 90 to 100 times the rope diameter to be certain there is no slipping with cyclic loading, which increases the diameter considerably and leaves a short center span. It was clear that this would also apply to the 40K sling legs. The grommet design permitted the use of the thimble and offered the lightest weight termination. The objective was to establish the efficiency, since the amount of Kevlar needed would be dictated by the stress concentration at the eye; i.e., the failure would occur at the thimble and not along the cable length. This is typical for grommet designed slings.

The grommet is a ring design, but not to be confused with the eyelet in a canvas or sail. Commonly made with steel rope, a continuous loop or ring is formed by splicing together two ends of a length of cable. With large thimbles designed for the steel grommet, one still has efficient sling design which is in common use. The Kevlar grommet was conceived not as a spliced ring of rope (splice is too long), but as a smaller basic strand wound over the thimbles to build up the size desired. In this way a standard strand of known properties could be used to make either a parallel, twisted, or counter-helix endless loop. The highest stress will, however, be at the loop apogee where only half the strands traverse. This means a good control is required of the strands during assembly. The design is such that the efficiency may be poorer than predicted in the analysis since we have a very exacting stress condition for a low elongation material.

The 25K sling leg grommets were made by forming 14-ft loops with strands of ct29/4x150. These strands are wax impregnated and twisted (0.3 tip) yarns of 15,000 denier (4/strand) of Kevlar 29. The 25K core has 10 strands cabled at a 7-in. right lay, and an outer layer of twelve strands of ct29/4x150 with a 14-in. left lay. Within each layer, the two ends of (4x150) strands are spliced.

An outer jacket of braided neoprene impregnated polyester is formed over the sling leg and loops, followed by a polyurethane coating fuzed to the braid. The loops were placed into No. 3 SLIP-THRU thimbles (BTC 745-G). Both ends were the same, with an overall length of 14 ft.

Preliminary tests were made to set up the processing of the grommet and then 10 test samples were built; Table 1 lists the test data. The average break strength of 39,000-lb $\pm$1920-lb, indicated the larger scatter of $\pm$5% compared to $\pm$2% in the 10K sling legs and an efficiency of 74% for this grommet type design. This is due to the stress concentration problem at the top of the eye on the thimble, and the small thimble radius. In laying up the cable, the total strands over the thimble are only half of the sling leg tensile member, which makes the smaller thimbles feasable to use but results in the lower efficiency.

This use of a Kevlar grommet design is a first, having been developed in this case because of the failure to foresee that a spliced loop would not fit the limited 14-ft length. There are a number of shorter splices that have been developed over the centuries - tuck splices, Flemish splices, and shorter terminations using swagged or squeeze fittings and resin potted terminations. But proving termination reliability is long and expensive. The grommet design has recognized restrictions based on long industrial experience with steel sling grommets, but it offers the lowest potential weight. It eliminates the separate operation of forming the termination after the rope is manufactured. No matter how high the rope quality, the tensile member is no better than the method of termination.

A short tensile member such as a sling leg will have more money invested in the two terminations than in the cable or rope. This will apply to all break strength ranges and particularly on very short, high-strength units such as for the 60,000-lb break strength legs in the 40K assemblies.

4.5 THE 40K SWL SLING LEG PRELIMINARY TESTS

The 40K sling legs were required to have a break strength of 56,000-lb minimum. The success with the 25K grommets suggested an increased strength by extropolation in number of core and outer strands. The same (4x150) strands could be used, allowing for torque balance by the number and lay angle as previously described in the analysis section. Accordingly, a series of 10 samples were made and tested, as required in the contract. These samples had a total of 34 strands of (4x150), which should give over 60,000-lb break strength assuming the same 74% efficiency obtained for the 25K sample.

The 40K sling leg data (Table 2) was consistent with the 25K results. Five values were below the required 56,000-lb, of which three were close (53,000, 54,000,and 55,000-lb), but two tests were well below the 70% efficiency. The latter turned out to be due to a failure to properly jacket and protect the Kevlar at the thimble. Excessive abrasion, coupled with the high compressive loading on the relatively small thimbles, results in a greater opportunity for erratic failure at lower strength levels. The first 10 show an average break strength of 55,650-lb, but short of the required 56,000-lb minimum.

Several improvements were then incorporated into the fabrication of the 16 sling legs made for proof testing, which reduced abrasion effects at the thimble. Unfortunately, during the proof testing (40% of break strength, or 22,400-lb, holding for 3 min.), the technician failed to use the required urethane sleeve between the loops and the thimbles. Thus, it became necessary to use the smaller, No.4, thimbles (to fit the grab hooks), and there was no space to put in the planned urethane sleeves. The proof testing at 22,400-lb on the bare No.4 galvanized steel forgings simply abraided the Kevlar at the loops.

TABLE 2. PRELIMINARY TENSILE TESTS - 40K SLING LEGS GROMMET DESIGN

First Series Break Strength (lb)	Second Series Break Strength (lb)	Third Series Break Strength (lb)
1 - 57,000	11 - 53,000	15 - 63,000
2 - 53,000	12 - 53,000	16 - 60,000
3 - 61,000	13 - 52,000	17 - 53,500 *
4 - 50,000 *	14 - 56,000	18 - 58,000
5 - 48,500 *		19 - 60,000
6 - 54,500		20 - 57,500
7 - 55,000		
8 - 58,500		
9 - 59,500		
10 - 59,000		

* Assembly error at one thimble

Note: There were eleven additional break strength tests on 40K sling legs, most of them checking units that had been prepared for delivery but damaged during proof testing after the first [illegible] preliminary sample tests.

These 16 damaged 40K sling legs were set aside since several break strength tests revealed low values of less than 50,000 lb. New sets of 40K sling legs were built and tested, but, for undetermined reasons, 70% or better efficiencies previously obtained could not be reproduced. In fact, efficiencies as low as 59% were obtained (tests #11, 12, 13.) This was attributed to the small radius of the thimble being used, but tests on No. 5 thimbles (tests 13 and 14) did not consistently give the higher values expected.

The new attempts to use the best techniques (test 15 and 16) indicate that sling legs can be built to the break strength required, but the eff ency of design is still below the 70% target, since it was necessary to go to a total o. 40 strands of (4x150).

The 40K sling legs were made as noted, using the same strands (ct29/4x150), but with a core of 18 strands of 9-in. right lay and the outer layer of 22 strands of 18-in. left lay. These were placed on No. 4 slip-through thimbles with an extruded polyurethane tube as an abrasion shield. The jackets and coatings were as previously described for the 25K sling legs.

Additional tests were then run as a further check of reproducibility (tests 17 through 20). In the one lower value, the outer strands had failed without any failure of the core. This was found to have been due to an error in assembling on the thimble.

5.0 DESIGN SPECIFICATIONS FOR SLING LEGS

The final assemblies with four sling legs each were made according to the specifications given below.

5.1 Sling Legs for 10,000 lb. SWL*Sling Assembly.
Overall length 14 ft $\pm$ 3 in., nominal $\frac{1}{2}$ in. diameter.
Minimum break strength of 17,200-lb
Construction: CORMAR IV, CH29/7x300/10x300 with polyester braided jacket, urethane impregnated. **

5.1.1 DuPont Kevlar 29, 15,000 denier, cordage finish. Two ends plied and twisted 0.4 tpi with hard wax impregnation to form strands. (Product code 300).

5.1.2 The core is to be seven strands at 6 in. lay (right), with each strand of 30,000 denier (2 ends of 15,000 d.yarn). Product code 7x300.

5.1.3 The outer layer is to be ten strands at 9 in. lay (left), with each strand of 30,000 d. (2x15,000 d.) Product code 10x300.

5.1.4 A braided polyester jacket of 0.05 in. will be manufactured over the cable and urethane impregnated. Product code PET/PU.

5.1.5 Twenty-five-foot lengths will be cut and five feet of jacket stripped from each end to prepare for spliced terminations 45 in. long.

5.1.6 Eye-splice terminations to be made using No. 2 SLIP-THRU forged steel thimbles (Brewer Titchner Company catalog no. 745-G No.2).

5.1.7 Spliced sections to be jacketed with polyester as in item 5.1.4.

5.1.8 Minimum break strength of 17,200-lb per Sling Leg.

5.2 Sling Legs for 25,000-lb SWL *Sling Leg Assemblies.
Minimum Break Strength of 37,800-lb, nominal 3/4 in. d.
Construction: CORMAR IV-G, CH29/10x600/12x600 PET/PU.(grommet design)

5.2.1 Materials and procedure to be as noted in 5.1.1 and ply 4 ends at 0.3 tpi. Product code 600.

* Safe Working Load

** The Product Code is as follows: CH is counter helix construction; 29 is DuPont Kevlar 29; 7x300 is 7 strands of 30,000 denier Kevlar 29.

5.2.2 The core is to be ten strands at 8 in. lay (right). Product code 10x600.

5.2.3 The outer layer is to be twelve strands at 14 in. lay (left), with each strand of 60,000 d. Product code 12x600.

5.2.4 Continuous strand wound core and outer layer formed over No.3 SLIP-THRU thimbles (BTC 745-G No. 3) Jacketing as in 5.1.4.

5.2.5 Minimum Break Strength of 36,000-lb per Sling Leg.

5.3 Sling Legs for 40,000-ib SWL Sling Leg Assembly.
Minimum Break Strength of 56,000-lb nominal 1 in. diameter.
Construction: CORMAR IVG-CH/22x600/18x600 PET/PU. (Grommet design)

5.3.1 Materials and procedure to be as noted in 5.2 above.

5.3.2 The core is to be twenty-two strands at 14 in. lay (right), with each strand of 4x15,000 d.

5.3.3 The outer jacket is to be eighteen strands at 24 in. lay (left), with each strand of 4x15,000 d.

5.3.4 Jacketing and termination procedure as above with No. 4 SLIP-THRU thimbles (BTC 745-G No.4).

5.3.5 Minimum Break Strength of 56,000-lb per sling leg.

Note: All sling legs were proof tested at 40% of break strength before final assembly and delivery.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

There is little problem in making the smaller sling legs (10K and 25K) with either the spliced loop or grommet design. The cable and sling leg efficiency can be well over 80% for the spliced loop design, which is consistent with previous experience on other cables.

The 40K grommet design required extensive testing on the smaller thimbles to be able to achieve both 70 to 80% efficiencies and a lower scatter in the test data.

The advantage of the grommet is the lower weight and cost over a spliced loop termination, which becomes increasingly larger and heavier with cables over 1 inch in diameter, and increasingly more cumbersome t produce using a splice.

All the final sling leg diameters were below the initial design requirements. The smaller grommet loop size, which is half the cross-sectional area of the tension length, permits smaller thimble sizes.

6.2 Recommendations

It is recommended that special thimble designs for the grommets be examined. For conventional steel rope grommets and slings, the inside radius is at least twice the conventional SLIP-THRU thimble types. This would require adaptors or redesign of the grab hooks.